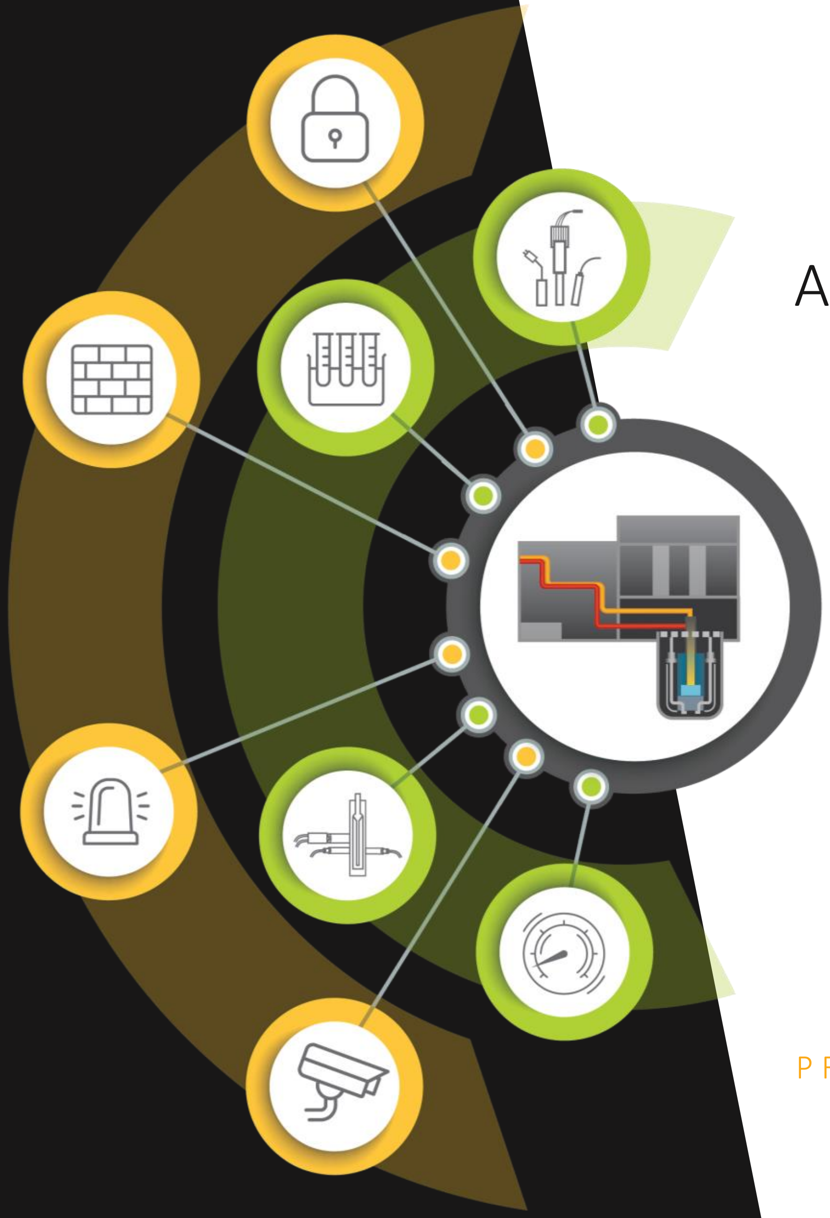

ADVANCED REACTOR SAFEGUARDS

# Using machine learning to improve efficiency and accuracy of burnup measurements at PBR reactors

PRESENTED BY

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# Motivations of the Work

- Burnup measurement is the key to deciding if the pebble should be discharged or recycled during the operation of a PBR reactor
- Height of photopeaks in gamma spectra related to various indicator isotopes such as $^{137}Cs$, $^{154}Eu$, etc., are often used for this measurement
- Source is complex and measurements are performed in less-than-ideal environment with self-shielding effects, strong radiation backgrounds and intervening material effects
- Burnup measurement faces two challenges:
  - High throughput
  - High accuracy

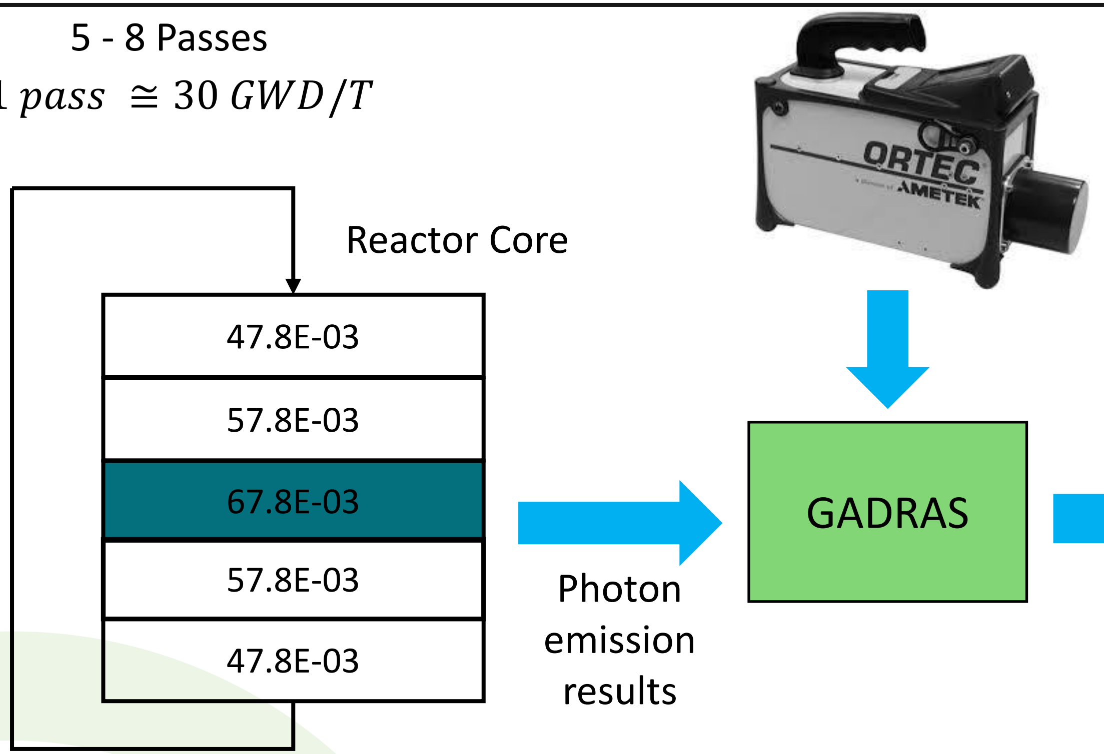
# Motivations of the Work (cont'd)

- Burnup measurement is a good question for machine learning (ML)
  - Large datasets can be produced
  - ML can take care of linear and nonlinear features in spectra
- Objectives
  - Create a workflow for modeling and simulation of both burnup and gamma-ray detection
  - Establish baseline datasets
  - Build ML models
  - Study performance of ML models

# Overall Process Flow

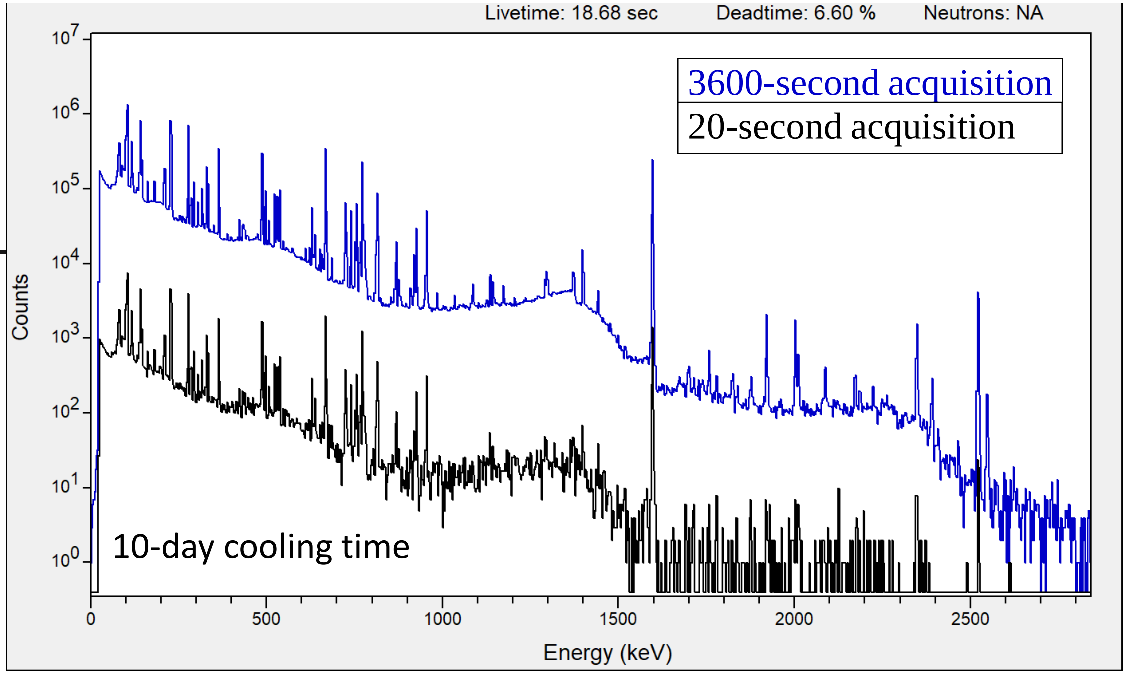
5 - 8 Passes

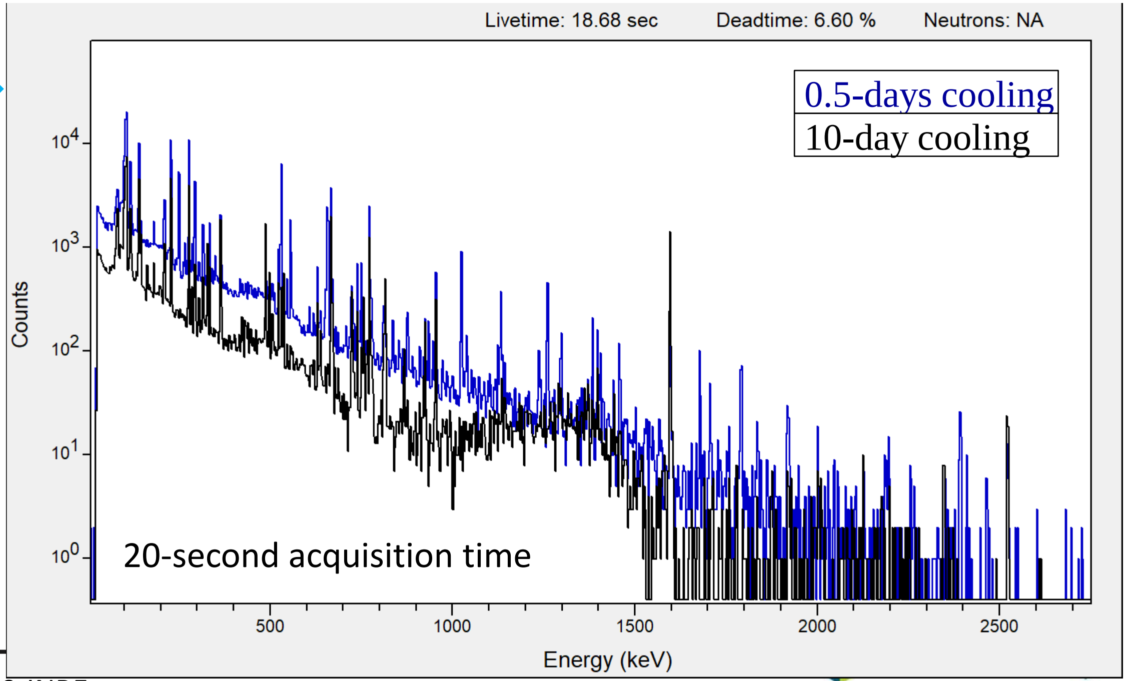
$1\ pass \cong 30\ GWD/T$




Serpent MC simulation

Parameters: composition, transit time, power and profile



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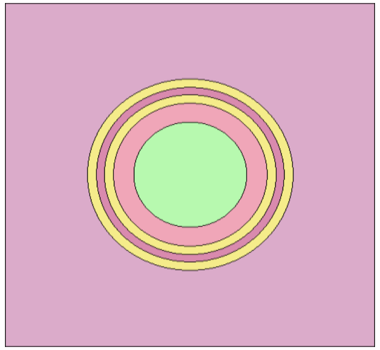
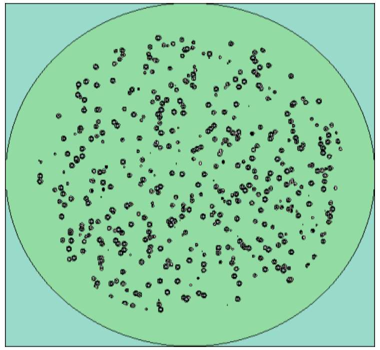
# Burnup and Source Modeling

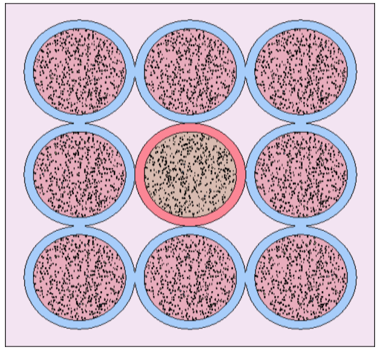
| Parameter | Value |
|---|---|
| Uranium Oxy-Carbide (UCO) Density (atoms/b-cm) | 6.9924E-02 |
| Buffer (C) Density (atoms/b-cm) | 5.2644E-02 |
| Pyrolitic Carbon (PyC) / Silicon Carbide (SiC) Density (atoms/b-cm) | ~9.5262E-02 |
| Number of Pebble/TRISO | 27/18857 |
| Pebble/TRISO radius (cm) | 3.000/0.0455 |
| Lattice configuration | 3 x 3 x 3 |
| Power ($MW_{th}$) | 280 |
| Boundary condition | Reflected/Periodic |
| Pebble/TRISO PF | 0.5200/0.1137 |
| Average residence time (days)/Cycles(passes) | 522/8 |
| Cooling time before spectral measurement (days) | 0, 0.5, 1, 2, 5, 10 |
| Data acquisition time (s) | 20, 3600 |



TRISO Kernel



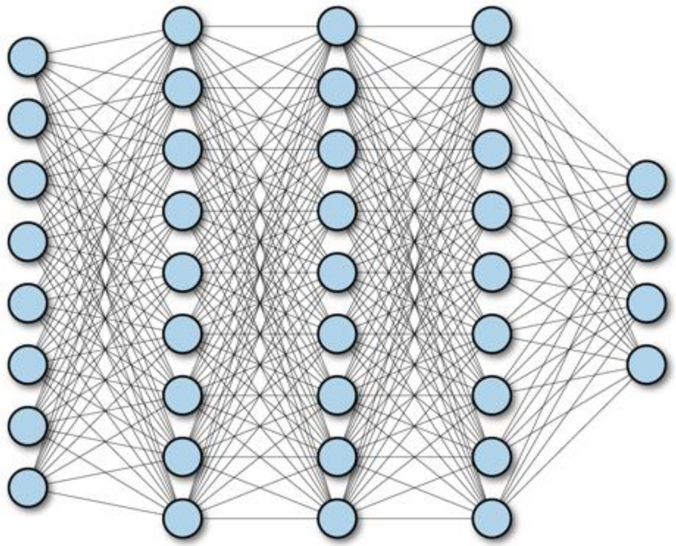
Single Pebble



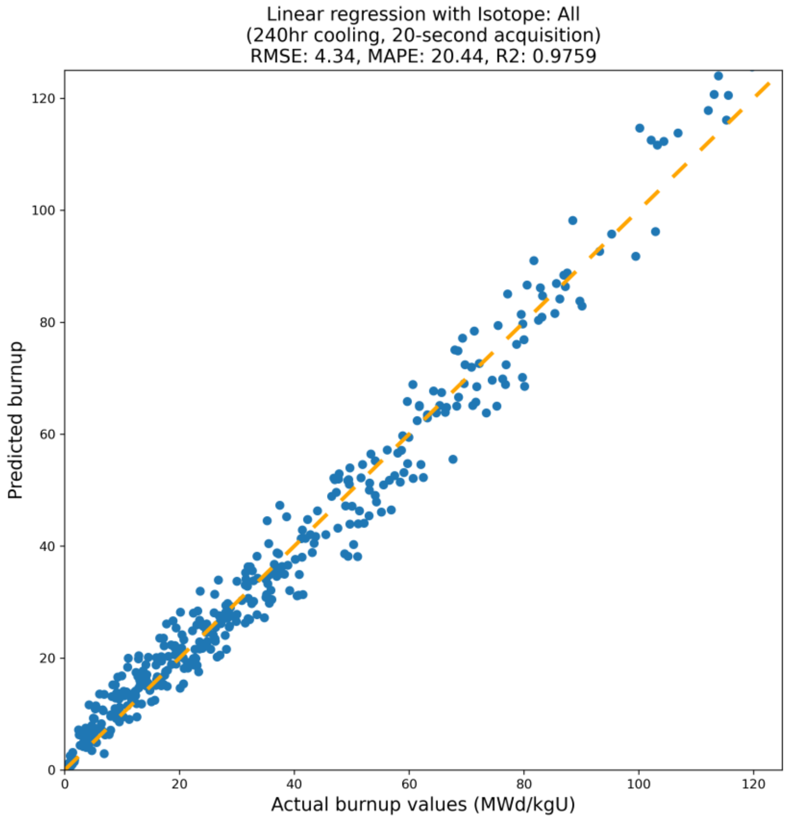
3x3x3 Pebble Lattice

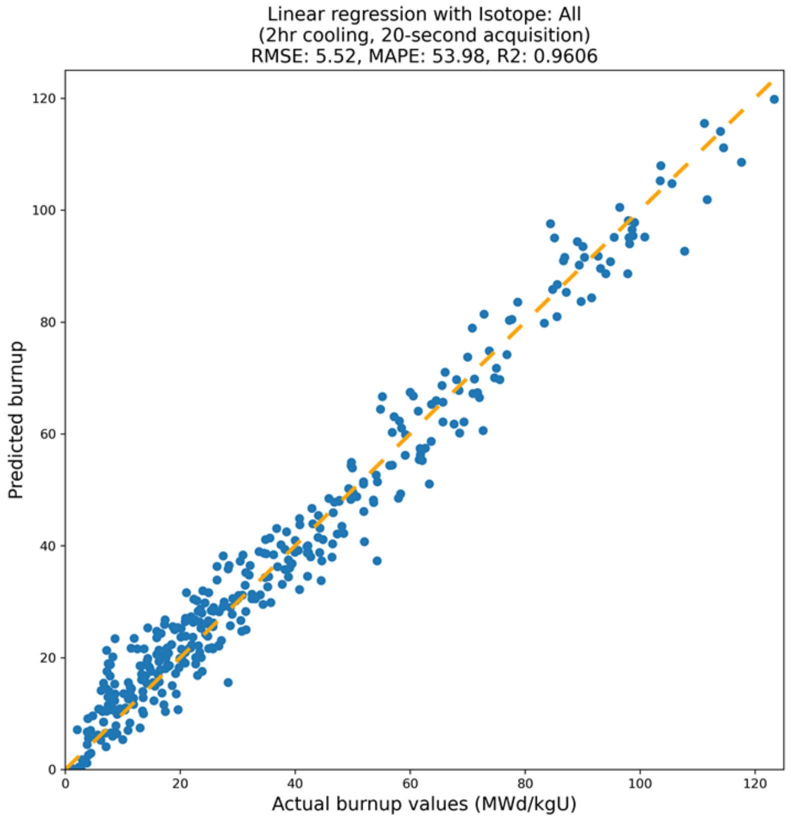
# MLP and Parameters

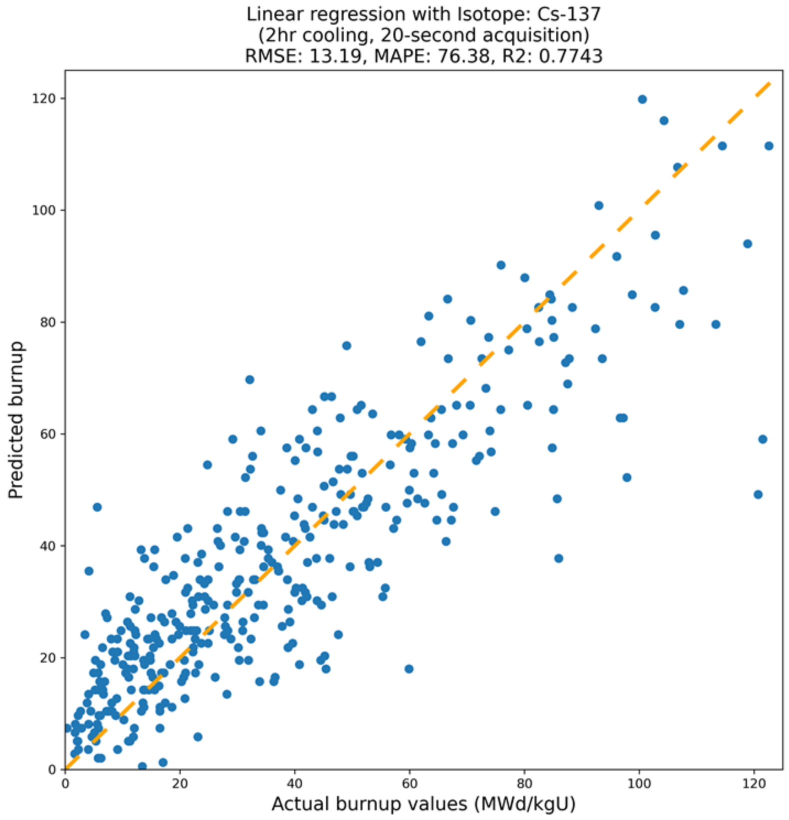
- MLP is a “classic” neural network
  - Architecturally simple
  - Extracts global features representations (because layers are fully connected)
- Parameters and hyperparameters
  - Connection weights and biases are learned during model training from annotated data (like standard regression)
  - Network shape (number and size of hidden layers) is architectural choice (“hyperparameter”) determined empirically
    - Other hyperparameters: learning rate, rate schedule, activation function, optimization algorithm and parameters, binning rate, dropout rate
    - 3-layer network with hidden layers of size 256 and 32 worked well



# Linear Regression with Reference Isotopes



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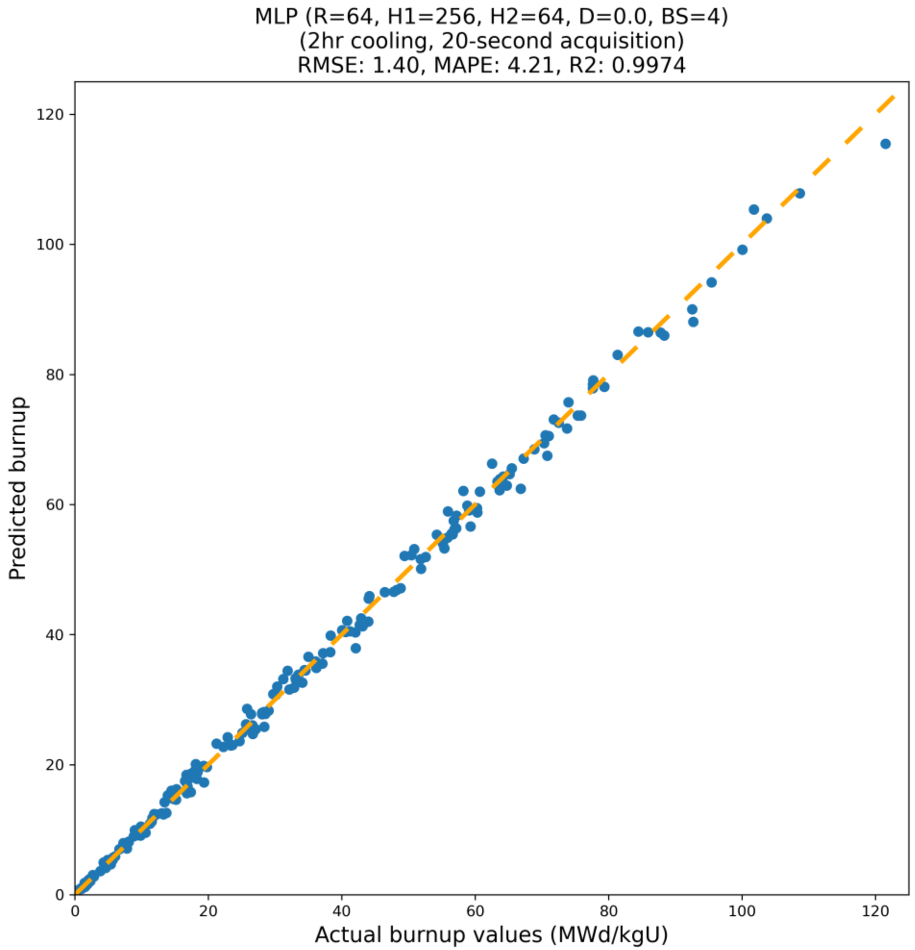
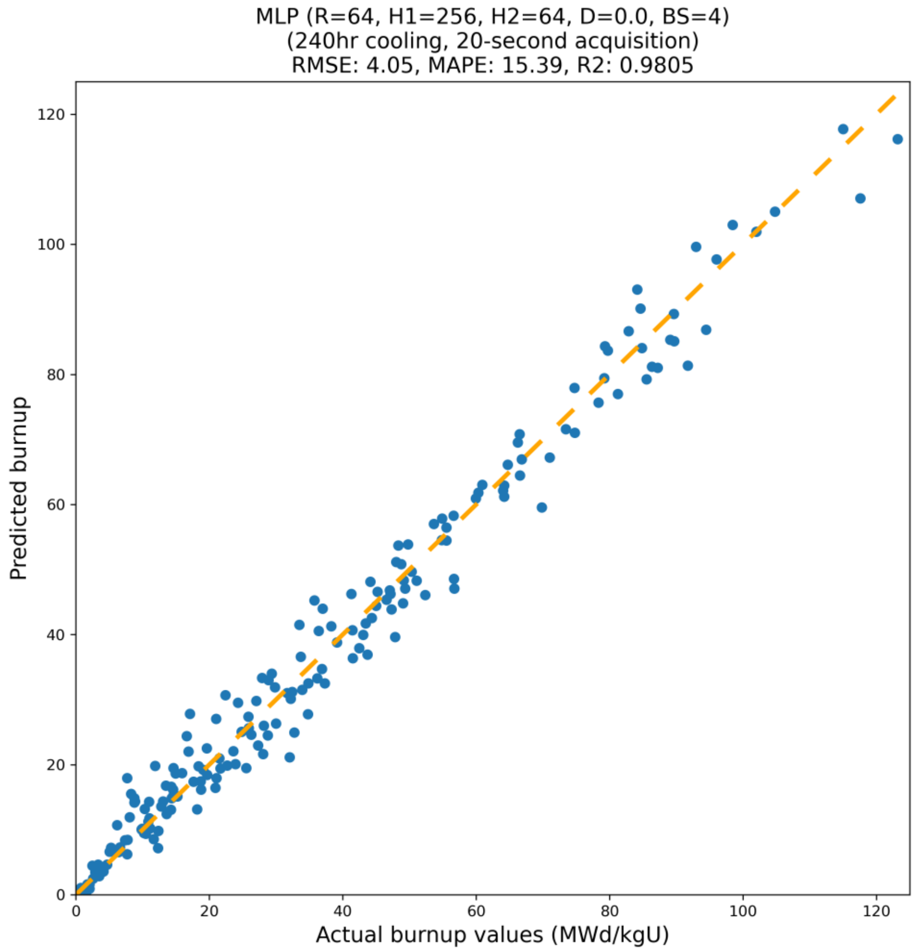
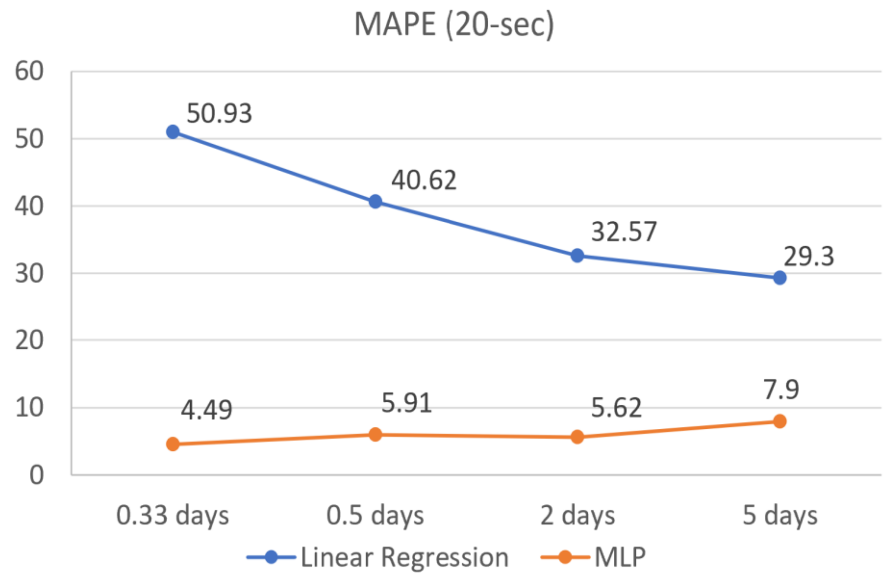
# ML Results


MLP (R=64, H1=256, H2=64, D=0.0, BS=4)
(2hr cooling, 20-second acquisition)
RMSE: 1.40, MAPE: 4.21, R2: 0.9974
Predicted burnup
Actual burnup values (MWd/kgU)
0
20
40
60
80
100
120


MLP (R=64, H1=256, H2=64, D=0.0, BS=4)
(240hr cooling, 20-second acquisition)
RMSE: 4.05, MAPE: 15.39, R2: 0.9805
Predicted burnup
Actual burnup values (MWd/kgU)
0
20
40
60
80
100
120

# Results

- A closer look at MAPE vs cooling time
- Performance of linear regression degrades as the cooling time gets shorter
- ML method can maintain nearly constant performance through different cooling time
- ML method has slightly better performance with shorter cooling time
- ML method sees signals related short lifetime isotopes as "features" while linear regression method suffers from such "noise".



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# Conclusions

- Both ML-based methods and photopeak-based linear regression method achieved high accuracy when the gamma-ray spectra contained negligible background radiation caused by short-lived fission products and minimal statistical errors.
- Under the measurement conditions that are being considered today for PBR operation, e.g., 2 days or less cooling time and 20-s acquisition time, the gamma spectra from burnup measurement is noisy.
- The proposed ML methods outperformed the conventional linear regression method significantly under these conditions.
- ML method can take advantage of short lifetime isotopes to improve the burnup measurement further.



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# Next Steps

- Finishing a study with low-cost, low energy resolution detectors (NaI and CZT)
- Improve the simulation model
  - Variance of pebbles and burnup process
  - Configuration of gamma measurement
  - Special cases, e.g., shutdown and restart
- Improve ML model to address needs coming up from the above research
- Validate the simulation/ML models
  - Reach out to PBR designers/researchers for additional datasets (Kairos, X-Energy, MIT, INL, VCU, …)
  - Conduct validation tests
- ML method for pebble identification
  - Unique ID
  - X-ray imaging

# Acknowledgement


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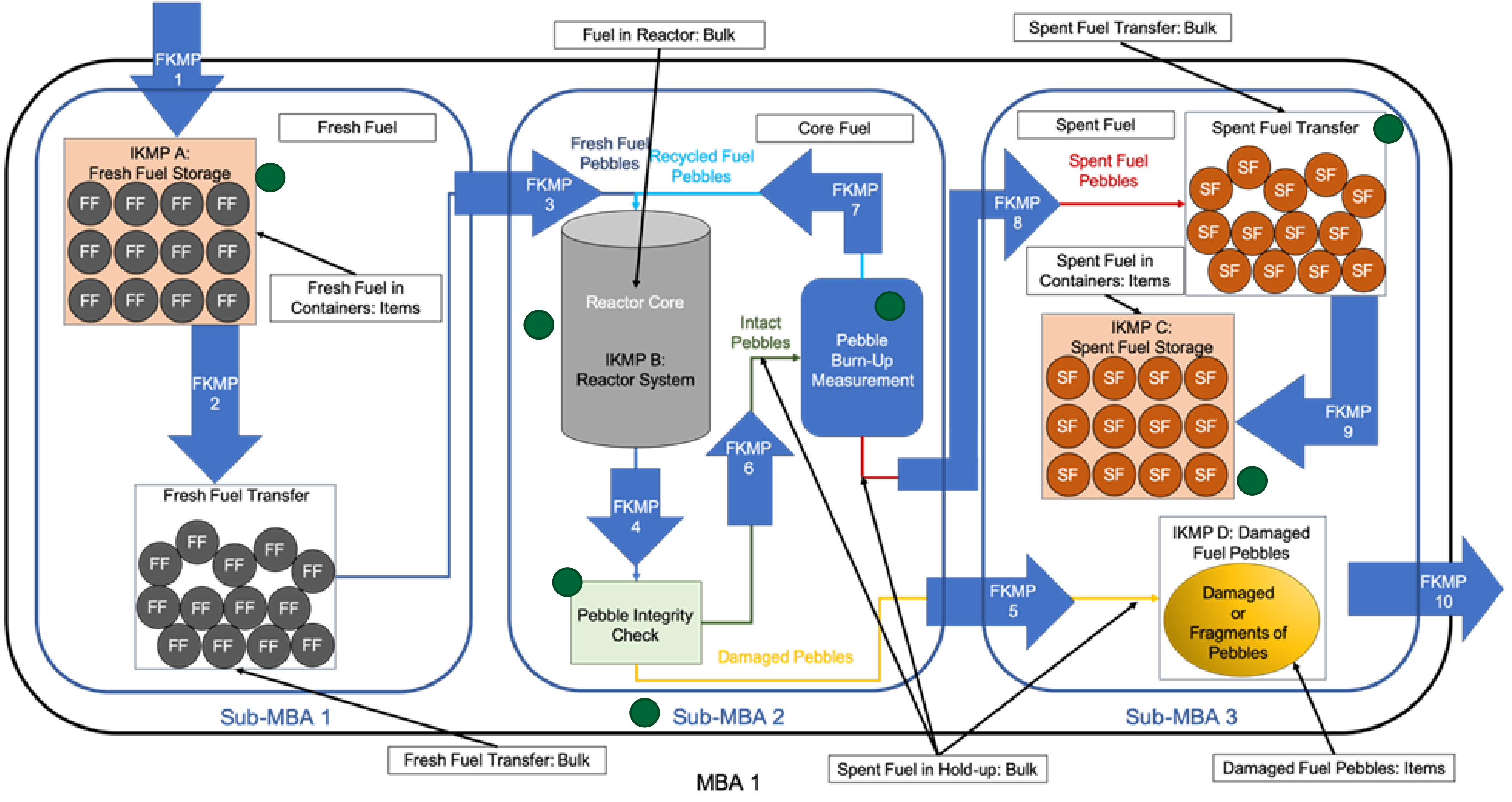
- The authors are grateful to Samuel E. Bays and Ryan Stewart from Idaho National Laboratory for their valuable suggestions in modeling pebbles and MC simulation in SERPENT.
- The authors also thank Per F. Peterson, Margaret Ellenson, Nicolas Zweibaum, and Nader Satvat from Kairos Power LLC. for sharing their burnup simulation results for validation of the results in this paper.

# Backup

# Potential Applications of ML for Safeguards at PBRs

We worked with Safeguards SMEs and PBR designers to identify the following areas that ML could potentially help improve efficiency and/or effectiveness of MC&A.

- **Improve burn-up measurements**
- Pebble integrity check
- Use transit times of selected pebbles to estimate/verify inventory in a reactor core
- Verify pebble inventory in the spent fuel containers
- Video surveillance in storage areas
- Using remote neutron measurement and operation log to estimate reactor power



# Isotope Energies

- Refence isotopes and gamma energies from T. Akyurek, et al., 2013
- Additional isotope energies from Interspec

| **Eu-154** | **Ru-106** | **Cs-137** | **Pr-144** |
|---|---|---|---|
| 123.07keV | 511.86keV | 661.657keV | 696.51keV |
| 1274.43keV | 621.93keV | | 2185.7keV |
| 723.3keV | | | 1489.16keV |
| 1004.76keV | | | |
| 873.18keV | | | |
| 996.29keV | | | |

Best suited candidate isotopes for three burnup applications with characteristic data.

| | Online analysis (group 1) | | | Interim storage analysis (group 2) | | | Long-term storage (group 3) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Isotope ($T_{1/2}$) (min) | Gamma energy (keV) | Gamma yields | Isotope ($T_{1/2}$) (days) | Gamma energy (keV) | Gamma yields | Isotope ($T_{1/2}$) (years) | Gamma energy (keV) | Gamma yields |
| 1 | $^{97}$Nb (72.1) | 1024.4 | 1.166E−06 | $^{132}$Te (3.20) | 49.72 | 2.286E−03 | $^{94}$Nb (20300) | 702.639 | 1.44E−09 |
| | | | | | 116.30 | 2.995E−04 | | | |
| | | 1268.62 | 1.505E−07 | | 228.16 | 1.345E−02 | | 871.114 | 1.44E−09 |
| | | 657.94 | 1.051E−04 | | | | | | |
| 2 | $^{132}$I (137.7) | | | $^{131}$I (8.0252) | 80.185 | 1.019E−06 | | | |
| | | 667.71 | 1.02E−04 | | 284.30 | 2.369E−06 | | | |
| | | 772.60 | 7.86E−05 | | 364.48 | 3.174E−05 | | | |
| | | 954.55 | 1.83E−05 | | 636.98 | 2.838E−06 | | | |
| | | | | | 722.91 | 7.021E−07 | | | |
| 3 | $^{85m}$Kr (268.8) | 151.195 | 4.424E−05 | $^{140}$La (1.68) | | | | | |
| | | 129.81 | 1.769E−07 | | 815.781 | 1.235E−05 | | | |
| | | 451.0 | 5.898E−09 | | 1596.203 | 4.968E−05 | | | |
| | | 304.87 | 8.258E−06 | | | | | | |
| 4 | $^{130}$I (741.6) | 536.07 | 1.54E−06 | $^{136}$Cs (13.16) | 340.55 | 1.468E−05 | | | |
| | | 668.54 | 1.49E−06 | | 818.51 | 3.472E−05 | | | |
| | | 739.51 | 1.27E−06 | | 1048.07 | 2.778E−05 | | | |
| 5 | $^{133}$I (1248) | 262.70 | 3.64E−06 | $^{103}$Ru (39.247) | | | | | |
| | | 422.903 | 3.16E−06 | | | | | | |
| | | 510.530 | 1.85E−05 | | | | | | |
| | | 617.978 | 5.51E−06 | | 39.76 | 1.672E−10 | | | |
| | | 680.252 | 6.59E−06 | | 53.275 | 9.048E−10 | | | |
| | | 706.575 | 1.52E−05 | | 294.98 | 6.809E−10 | | | |
| | | 768.360 | 4.67E−06 | | 443.80 | 8.105E−10 | | | |
| | | 856.278 | 1.25E−05 | | 497.08 | 2.151E−07 | | | |
| | | 875.328 | 4.57E−05 | | 557.04 | 2.014E−09 | | | |
| | | 1052.39 | 5.63E−06 | | 610.33 | 1.361E−08 | | | |
| | | 1236.44 | 1.52E−05 | | | | | | |
| | | 1298.22 | 2.38E−05 | | | | | | |
| | | 529.870 | 8.83E−04 | | | | | | |
| 6 | | | | $^{95}$Nb (34.985) | 204.12 | 3.181E−10 | | | |
| | | | | | 561.88 | 1.060E−10 | | | |
| | | | | | 765.803 | 1.058E−06 | | | |
| 7 | | | | $^{95}$Zr$^{a}$ (64.032) | 235.69 | 3.430E−06 | | | |
| | | | | | 724.193 | 5.624E−04 | | | |
| | | | | | 756.729 | 6.909E−04 | | | |
| 8 | | | | $^{134}$Cs (753.72) | 563.243 | 3.711E−09 | | | |
| | | | | | 569.32 | 6.819E−09 | | | |
| | | | | | 604.72 | 4.329E−08 | | | |
| | | | | | 795.83 | 3.791E−08 | | | |
| | | | | | 801.945 | 3.857E−09 | | | |
| | | | | | 1365.186 | 1.337E−09 | | | |

T. Akyurek, et al., Review and characterization of best candidate isotopes for burnup analysis and monitoring of irradiated fuel, 2013.